



Indirect evidence of wind erosion trends on the Southern High Plains of North America

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Abstract

Detecting and quantifying changing regional patterns of wind erosion activity is complicated by a lack of long-term records of direct wind erosion measurements. Here, we attempt to piece together indirect evidence of changing wind erosion activity on the Southern High Plains. Sources of indirect evidence include visibility-based observations of blowing dust as well as past measurements of ambient particulate matter concentration. Both the visibility record and particulate matter record suggest independently that there have been significant declines in blowing dust during the last 40 years. There are three key factors that may have contributed to the observed reduction of blowing dust—natural climatic variations, changing land use, and improved agricultural practices. Historical climatic records suggest that there have been no appreciable climate shifts that could account for the observed decline in blowing dust. Although it is not possible to rule out land use as a factor in the reduction of blowing dust, one can point to periods when land use changed very little while annual dust levels decreased significantly. Overall, the relatively minor changes in land use, including the removal of land from production, cannot fully account for the magnitude of the observed reduction of ambient dust levels on the Southern High Plains. We are left to conclude that the adoption of improved agricultural practices has played a crucial role in reducing wind erosion activity and dust emissions on the Southern High Plains. Published by Elsevier Science Ltd.

1. Introduction

Agricultural practices and land-use patterns tend to evolve as farmers react to economic forces, adopt new technologies, and adjust to varying climatic conditions. In the process an entire region can be gradually transformed. Such regional transformations can have either positive or negative impacts on the environment.

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Historians generally agree that the transformation of the Southern High Plains from rangeland to cultivated fields during the early part of the 20th century significantly increased wind erosion activity (Worster, 1977; Hurt, 1981). This period of environmental transformation culminated in the Dust Bowl of the 1930s—a low point in American environmental history (Worster, 1979; Brooks and Emel, 2000).

Following the Dust Bowl, the transformation of the Southern High Plains has continued in more subtle ways, as agricultural practices and land-use patterns continue to evolve due to many factors. Research and education have led to improvements in agricultural practices and agricultural machinery (Todhunter and Cihacek, 1999). Government programs have encouraged soil conservation and the retirement of marginal land (Ervin and Lee, 1994). Improved pumping technology has led to a major shift from dryland to irrigated agriculture, as the Ogallala Aquifer has been increasingly tapped for irrigation purposes (Opie, 1993).

There is no doubt that the post-Dust Bowl transformation of the Southern High Plains has had and continues to have an impact on wind erosion rates. However, quantifying regional wind erosion trends has proven difficult due to the fact that long-term records of soil loss or other direct measurements of wind erosion processes have not been systematically collected. Because we are not afforded the luxury of going back in time to gather additional information, we must attempt to glean information from existing and often imperfect data sources involving indirect methods of wind erosion monitoring.

Indirect methods include observations of blowing dust either in the form of particulate matter sampling (Offer and Goossens, 2001; Stout, 2001) or visibility observations (Pecille, 1973; Goudie, 1983; Wigner and Peterson, 1987; Todhunter and Cihacek, 1999). In semi-arid agricultural regions that lack significant industrial sources of particulate matter, elevated levels of particulate matter generally indicate blowing dust associated with regional-scale wind erosion activity. One expects low dust levels to be associated with low wind erosion activity and relatively high dust levels to be associated with relatively high wind erosion activity. More importantly, one expects that if a region becomes less erodible with time, then reductions in wind erosion activity will be reflected in a general reduction of ambient dust levels. Thus, long-term records of blowing dust can provide valuable information regarding changing regional wind erosion activity in some regions (Orgill and Sehmel, 1976; Goudie and Middleton, 1992; Todhunter and Cihacek, 1999).

Here an attempt is made to piece together evidence of wind erosion trends associated with changing agricultural practices within the Southern High Plains. These data include surface observations of blowing dust by National Weather Service (NWS) observers, ambient particulate matter samples collected by various local, state, and federal regulatory agencies, and recent particulate matter samples collected by the USDA-Agricultural Research Service (USDA-ARS).

2. Physical setting

Located at the southern end of the Great Plains (Fig. 1), the Southern High Plains, also known as the Llano Estacado, is an immense elevated plateau of approximately

78,000 km², bounded on three sides by “caprock” escarpments 50–200 m high (Reeves and Reeves, 1996). The western and northern escarpments separate the plateau from the Pecos and Canadian River valleys, respectively. Spring sapping and headward erosion by tributaries of the Red, Brazos, and Colorado Rivers have etched away at the eastern escarpment, which separates the Southern High Plains from the Rolling Plains of Texas and Oklahoma (Holliday, 1995). To the south, the plain passes without sharp physiographic break into the Edwards Plateau of central Texas. The surface of the Southern High Plains appears flat and featureless but there is a gentle, almost imperceptible, slope to the southeast; approximately 2 m/km (Wendorf, 1961). Surface elevations vary from 1700 m in the northwest to 750 m in the southeast (Gustavson and Holliday, 1999). Lubbock is approximately 1 km above sea level.

Outside of the urban areas, the landscape is significantly impacted by agriculture. Cropland accounts for 80% of the total surface area within Lubbock County and cotton acreage accounts for 87% of harvested cropland (USDA-NASS, 1997). Each year, cotton fields in the Southern High Plains pass through a regular cycle. Planting begins in May and is completed by mid-June. As cotton plants emerge, they begin to provide minimal ground cover and wind erosion protection. As plants reach the growth stage called first square, the point at which cotton plants begin setting blooms, individual plants have sufficient height and adequate leaf and stem area to provide significant protection of the soil surface. In the Southern High Plains, squaring begins in late June and finishes in mid-July. Between squaring and harvest, most fields have adequate ground cover to protect the soil surface for all but the most extreme wind conditions. Protective vegetative cover is removed during harvest, which takes place from October to December. After harvest, fields lie bare and exposed from late winter through spring. Unfortunately, winds tend to peak during late winter and spring when cotton fields are bare and most susceptible to wind erosion (Stout, 2001).

From a surface-processes perspective, the Southern High Plains may be considered a vast irregularly shaped erodible surface surrounded by relatively stable land. Although grass fires, industrial sources, and unpaved roadways may occasionally add to the atmospheric dust load, dust generated by wind erosion is the primary source of particulate matter within the region. During periods of strong wind, the Southern High Plains becomes a source area for dust emissions; thus, ambient dust levels measured at a point within this source area are positively correlated with wind erosion activity (Stout, 2001).

3. Visibility observations of blowing dust

United States NWS Surface Weather Observations (available on microfiche from the National Climatic Data Center) provide detailed information on meteorological phenomena at first-order weather stations. In addition to hourly weather data, observers recorded additional information for a variety of conditions. One of these was visibility reduction due to blowing dust. Observers recorded the time that

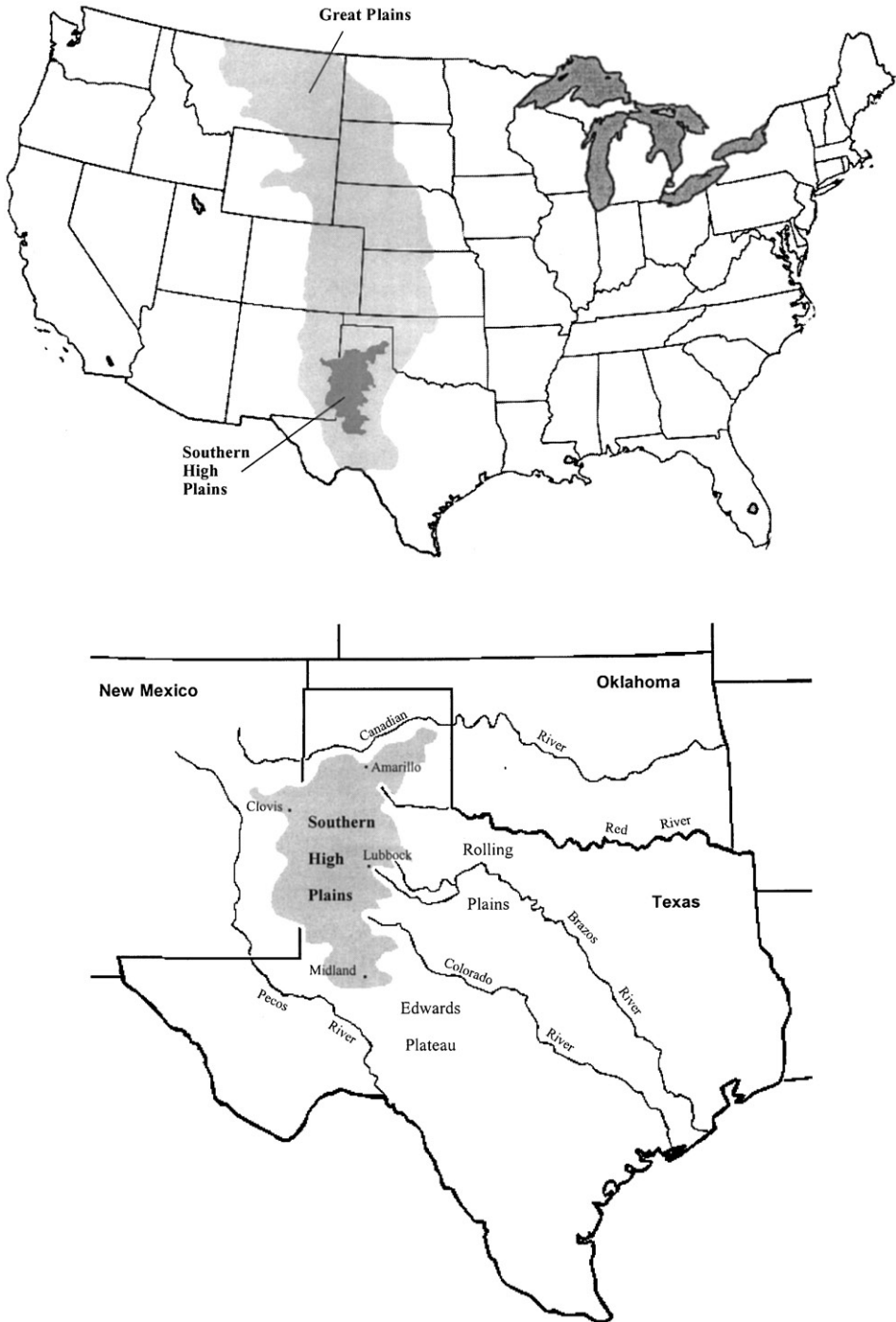


Fig. 1. (a) Southern High Plains: a distinct physiographic subregion of the Great Plains. (b) Southern High Plains as defined by [Holliday \(1995\)](#) showing its location within west Texas and eastern New Mexico.

visibility fell below 7 miles (11.3 km), establishing the start of a blowing dust event, and they entered the letters “BD” to differentiate between blowing dust and other causes of reduced visibility such as fog or smoke. During the dust event, observers continually noted changes in visibility. As the dust storm abated and visibility once again exceeded seven miles, the time was recorded, establishing the end of the dust event. Thus, the duration of each dust event can be determined based on the recorded start and end times.

Lubbock Weather Service observations of blowing dust and visibility extend from 1947 through 1993. In 1994, modernization efforts brought about a shift from human observers to optical visibility sensors with the introduction of the Automatic Surface Observing System (ASOS). Optical visibility sensors provide a more precise measure of visibility than human observers can provide; however, unlike human observers, optical sensors that are based on light scattering cannot distinguish between blowing dust, blowing snow, falling snowflakes, intense rainfall, thick fog or drifting smoke. Thus, following 1993 it is still possible to determine the total number of hours of reduced visibility each year but it is more difficult to distinguish the fraction of time specifically associated with blowing dust.

Wigner (1984) and Lee et al. (1994) independently analysed surface weather observations for Lubbock, noting all of the blowing dust events and their duration. Wigner (1984) examined the period from 1947 to 1983 and determined the number of hours of blowing dust by summing the duration of all dust events each month and then rounding each monthly total to the nearest hour. As a result of the rounding process, months with less than 30 min of blowing dust were rounded down to zero hours. Ervin and Lee (1994) added detail to the data set by extending the analysis to 1991 and by including all dust events regardless of length (no rounding). As part of the present study, we have extended the analysis to the entire 47-year record from 1947 through 1993 (Fig. 2).

An examination of Fig. 2 reveals that there has been a general reduction in the number of hours of blowing dust with time. Values typically exceeded 200 h of blowing dust per year in the 1940s and 1950s whereas they remained below 50 h per year in the late 1980s and early 1990s. Fitting a trendline to this 47-year data record yields a negative slope of -4.6 h of blowing dust per year.

Visibility-based observations of blowing dust should be viewed as only one form of evidence suggesting environmental change on the Southern High Plains. Conclusions drawn from surface visibility observations would be strengthened if supported by other independent sources of evidence. What follows is an examination of existing records of direct particulate matter measurements as possible sources of additional information.

4. Past particulate matter sampling

Systematic national efforts to monitor air pollution in the United States began in 1953, when the Public Health Service, in cooperation with local and state agencies, began sampling total suspended particulates (TSP) in ambient air using high-volume

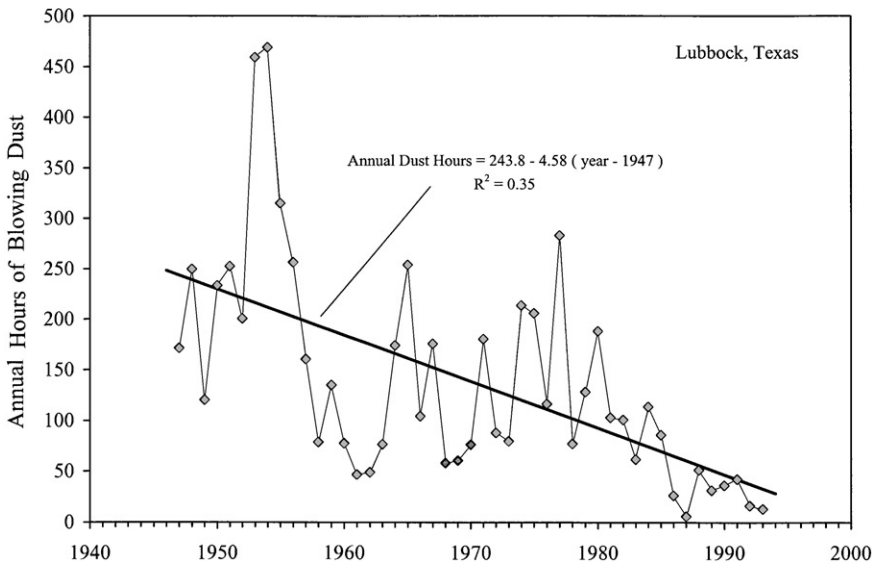


Fig. 2. Annual hours of blowing dust from 1947 to 1993 as reported by surface weather observers at the Lubbock office of the NWS.

samplers in 17 cities (EPA, 1969). Two years later, the Air Pollution Control Act of 1955 authorized the Public Health Service to provide training programs and technical assistance to state and local agencies (Godish, 1985). By 1956 particulate matter sampling had expanded to 66 communities in 14 states nationwide (Goklany, 1999). These early efforts eventually led to the creation of the National Air Sampling Network (NASN) in 1957, which expanded the existing network to 185 urban and 48 rural stations (EPA, 1969).

Lubbock, Texas was designated as part of the NASN in 1961 (Cowgill, 1970). The first TSP sample was obtained on January 8, 1961 using a high-volume sampler mounted on the roof of the central fire station. The full Lubbock TSP record extends from January 1961 through August 1987, when the National Ambient Air Quality Standard for TSP was replaced by the PM_{10} standard nationwide. This shift in regulatory focus was necessitated by the recognition that particulate matter less than $10\mu m$ (PM_{10}) is a better indicator of health impact than is TSP, because smaller particles are more likely to be inhaled deeply into the lungs (Goklany, 1999).

Past particulate matter concentration measurements were obtained from the Texas Natural Resource Conservation Commission (TNRCC). Daily TSP values were averaged to obtain annual-average TSP values for each full year of measurement. The results reveal that annual TSP concentration can vary markedly from 1 year to the next (Fig. 3). There is also a significant downward trend indicating a general reduction of TSP concentration with time; over the 26 full years of measurement from 1961 to 1986 the average annual TSP concentration decreased by 50%.

Annual dust hours and annual TSP concentration are plotted together in Fig. 4. The records overlap from 1961 to 1986, when annual hours of blowing dust and

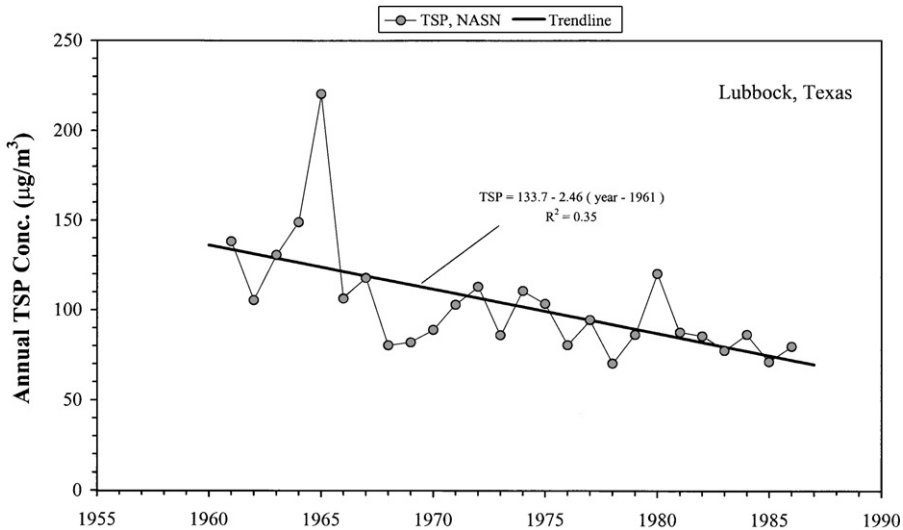


Fig. 3. Annual TSP concentration measured as part of the NASN from 1961 to 1986 in Lubbock, Texas.

annual TSP concentration were both measured. A visual inspection of Fig. 4 reveals that the dust-hour record roughly mimics the TSP record; with few exceptions, peaks and troughs in the dust-hour record match peaks and troughs in the TSP record. A test for correlation between annual dust hours and annual TSP concentration from 1961 to 1986 was performed using Spearman's rank correlation coefficient, a nonparametric test for general association between data pairs. The resulting value of 0.4 indicates an imperfect correlation between the visibility record and the TSP record. The lack of correlation may be related to the subjective nature of visibility measurements, which depends upon the judgement of a human observer and the observer's ability to detect distant objects.

5. Recent particulate matter sampling

In 1997, a team of scientists and technicians at the Lubbock office of the USDA-ARS began to collect TSP samples to compare present-day ambient dust levels to those collected from January 1961 to August 1987 and to further define ambient dust trends. Samples were collected using sampling systems that incorporate commercially available low volume samplers (Stout, 2001). Two sampling systems were constructed. The first unit began operation in March of 1997 at Lubbock Lake Landmark, an archaeological preserve located at the northern edge of the city of Lubbock. The second unit began operation in March of 1999 at Reese Center, located at the western edge of Lubbock.

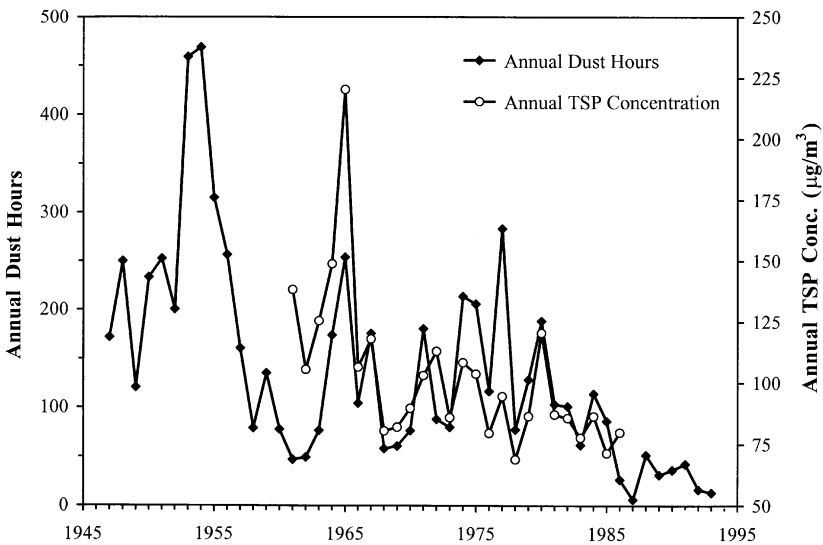


Fig. 4. Annual TSP and reported annual hours of blowing dust plotted together.

5.1. Sampler design and site bias

Because the sampling sites were located a few miles to the north and west of the Lubbock central fire station and because sampler designs were not identical to those used from 1961 to 1987, one naturally wonders whether these two factors might introduce bias. We tested for the combined influence of sampler type and sampler location by comparing PM_{10} measurements collected with low volume samplers at Lubbock Lake and PM_{10} measurements collected with high volume samplers on the roof of the central fire station. From 1996 through 1997, the TNRCC collected PM_{10} samples at a frequency of one sample every other day using high volume samplers mounted on the roof of the central fire station. For an 18-month period beginning 23 March 1996, the USDA-ARS collected a continuous series of PM_{10} samples using low volume samplers at the Lubbock Lake site (Stout, 2001). During this period there were a total of 216 common days where PM_{10} samples were collected concurrently at both sites. Taking the average PM_{10} concentration using only common days yields a value of $18.5 \mu\text{g}/\text{m}^3$ at the central fire station and $19.9 \mu\text{g}/\text{m}^3$ at the Lubbock Lake site, a difference of less than 8%. These data also exhibit a strong daily correlation between PM_{10} measured at Lubbock Lake and the central fire station—the calculated correlation coefficient was 0.82. These results suggest that if both sampler designs provide an accurate measure of particulate matter concentration and both sites provide a true measure of regional dust conditions then the average dust concentration is not significantly influenced by the site location or the specific sampler design.

5.2. Summary of TSP results

The USDA-ARS annual TSP concentration measurements from 1998 to 2001 are plotted along with TSP data collected as part of the NASN from 1961 to 1986 (Fig. 5). The USDA-ARS values fall near the trendline that was fit to the data collected from 1961 to 1986. Fitting a trendline through all of the annual TSP values yields a slope of $-2.6 \mu\text{g}/\text{m}^3$ per year a value that is slightly more negative than the $-2.4 \mu\text{g}/\text{m}^3$ per year slope of the trendline fit to the 1961–1986 data alone. Thus, recent USDA-ARS TSP measurements confirm that ambient dust levels on the Southern High Plains have continued to decline appreciably after 1986.

Conclusions drawn from available TSP records suffer from an 11-year data gap from 1987 through 1997 due to the fact that TSP sampling was replaced by PM_{10} sampling during this period. What follows is an examination of existing PM_{10} records as a possible source of additional information that could be used to establish dust trends where TSP measurements are not available.

6. PM_{10} measurements

PM_{10} samples were collected in the Lubbock area through a joint program involving the Texas Air Control Board (later absorbed into the TNRCC) and the US Environmental Protection Agency. The first Lubbock PM_{10} sample was collected on January 1, 1987 using a high volume PM_{10} sampler mounted on the roof of the central fire station. After this date PM_{10} samples were collected on a nominal

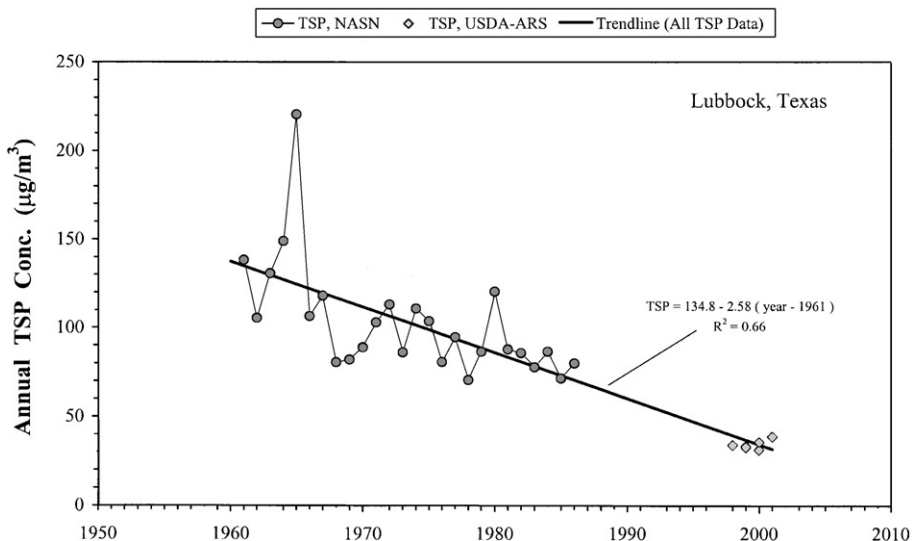


Fig. 5. Annual TSP concentration measured as part of the NASN and more recent measurements by the USDA-ARS. Regression line is fit to all data. The slope of the regression line fit to the NASN and USDA-ARS data is nearly identical to the slope of the regression line fit to the NASN data alone (Fig. 3).

schedule of one sample every 6 days. Annual-average PM_{10} concentration was calculated for each year of measurement. Overall, the results (Fig. 6) suggest that PM_{10} concentration has declined appreciably from 1989 to 1999. Following 1999, annual PM_{10} values have increased slightly, possibly indicating that ambient dust levels have reached a lower limit.

6.1. Estimated TSP

For an 8-month period, from January to August 1987, both TSP and PM_{10} samples were collected with high-volume samplers on the roof of the Lubbock central fire station. Measured PM_{10} and measured TSP are plotted together in Fig. 7. Using a total of 35 common days when both quantities were measured, the average ratio of TSP and PM_{10} is approximately 2. This ratio was used to estimate TSP by adjusting measured PM_{10} values as

$$\text{Estimated TSP} \cong 2 \times PM_{10}. \quad (1)$$

Estimated TSP and measured TSP are plotted together (Fig. 8). The results suggest that Eq. (1) adequately adjusts PM_{10} values so that they closely approximate TSP values (Fig. 8). A test for correlation between measured and estimated TSP was performed using Spearman's rank correlation coefficient. The resulting value of 0.73 suggests a fairly strong yet imperfect correlation between measured and estimated TSP. There are many possible reasons why individual data pairs may agree on some days and not on others. First, there may be random errors associated with the

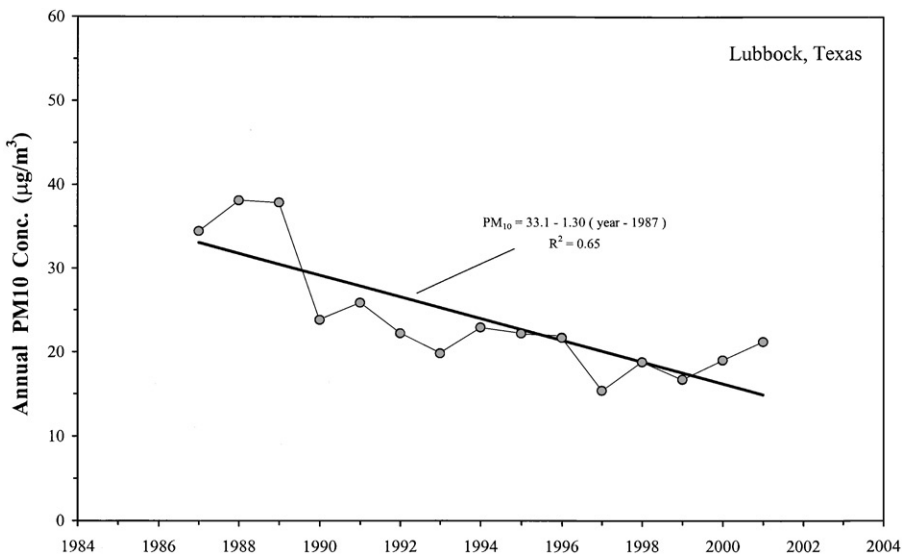


Fig. 6. Annual PM_{10} concentration as measured from 1987 to 2001 by the Texas Air Control Board (TACB) and the TNRCC.

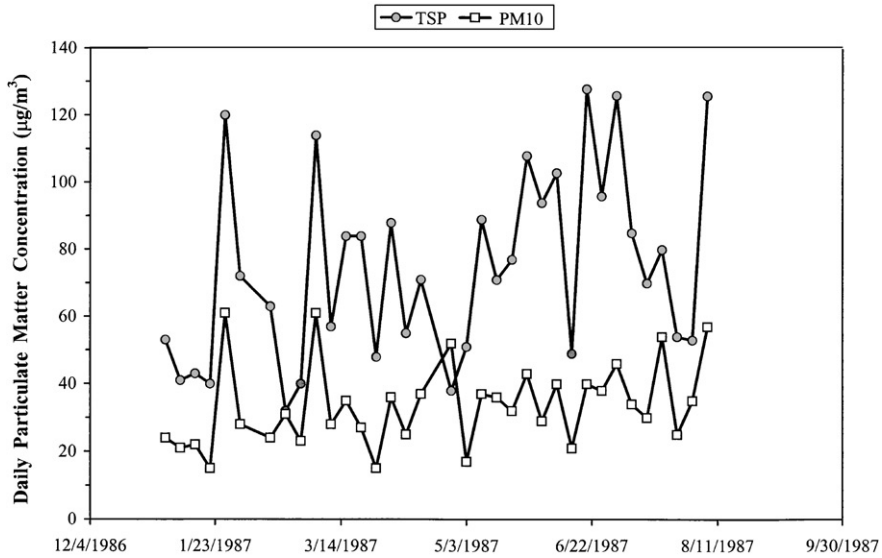


Fig. 7. TSP and PM₁₀ measured from January to August 1987 in Lubbock, TX.

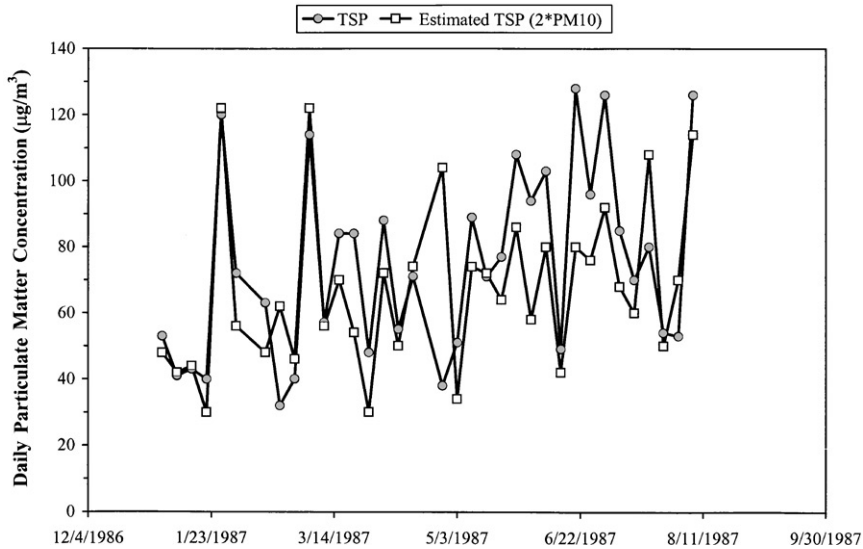


Fig. 8. Measured TSP and “estimated TSP” values derived from PM₁₀ measurements obtained from January to August 1987.

measurement of either TSP or PM₁₀. Second, the size distribution of particulate matter in the atmosphere may naturally vary from day to day causing the TSP to PM₁₀ ratio to shift somewhat. Nevertheless, errors between measured and estimated TSP are sometimes negative and sometimes positive so that over a long period they

tend to cancel out. This suggests that the estimation of long-term average TSP from a series of daily PM_{10} measurements may be more reliable than the estimation of daily TSP values.

Daily PM_{10} measured from 1987 to 2001 were adjusted using Eq. (1) then averaged to obtain estimated annual TSP. Measured TSP and estimated TSP are plotted together in Fig. 9. TSP values estimated from the existing PM_{10} record fall near the overall trendline established by the measured TSP record alone. The combined plot (Fig. 9) provides a more complete picture of the decline of blowing dust on the Southern High Plains over the last 40 years. Results suggest that ambient dust levels in the Lubbock area have dropped to less than one-quarter of the typical annual concentration four decades earlier. Because wind erosion is the primary source of particulate matter in the region, one can infer that declines in regional wind erosion activity have contributed significantly to the observed decline in ambient dust levels:

7. The role of climate

There are several factors that may have contributed to the observed reduction of blowing dust on the Southern High Plains during the last 40 years. Farmers may have collectively improved their agricultural practices to the point that fields within the region are less susceptible to wind erosion or they may have changed regional land-use patterns. It is also possible that natural climatic variations have influenced

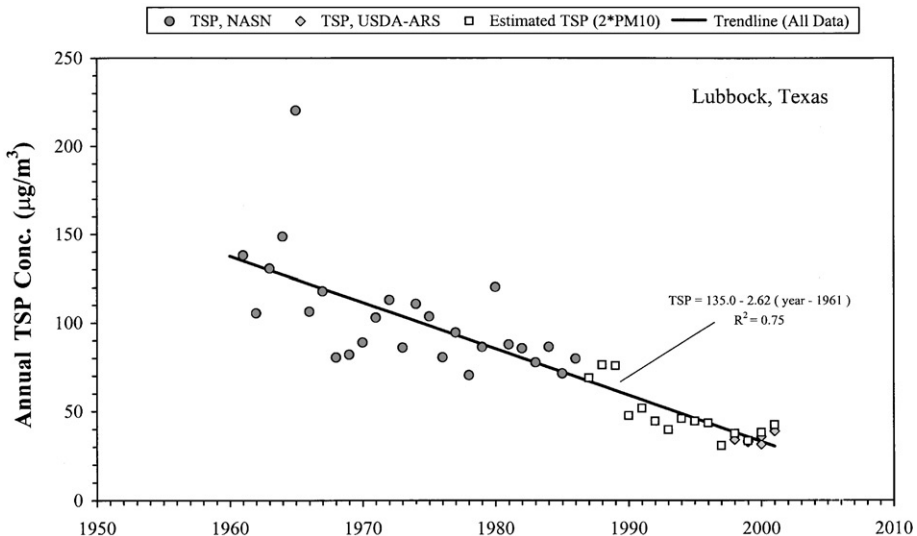


Fig. 9. Full TSP record for Lubbock including TSP data collected as part of the NASN, TSP data collected by the Agricultural Research Service (USDA-ARS), and TSP data estimated from PM_{10} measurements obtained by the TACB and TNRCC.

the frequency and intensity of wind erosion events. What follows is an attempt to ascertain the role of climate.

Lubbock climate information was obtained from a National Oceanographic and Atmospheric Administration (NOAA) publication “Local Climatological Data”, which summarizes NWS observations of climatic variables. With respect to wind erosion, variables of importance include wind speed, precipitation and relative humidity. Wind provides the driving force for the wind erosion process whereas precipitation and relative humidity are important factors that affect soil moisture and thereby influence the critical threshold of the regional surface.

The anemometer used to measure wind speed at the Lubbock airport has been mounted at various heights in the past ranging from 19.8 to 7.6 m. For this analysis, all wind data was adjusted to a common height of 10 m, assuming a 1/7-power-law profile (Simiu and Scanlan, 1978). Height-adjusted daily wind speed values were averaged to obtain annual wind speed for each year from 1961 to 2001 (Fig. 10).

Annual wind speed shows no major trend from 1961 to 2001 (Fig. 10). Over the past 40 years, annual wind speed has varied from a minimum of 4.7 m/s in 1979 to a maximum of 6.0 m/s in 1990 with an average value of 5.5 m/s and a standard deviation of 0.3 m/s. Certainly, there has been no appreciable reduction of wind speed that could account for the substantial decline in ambient dust levels (compare Figs. 9 and 10). This suggests that factors other than wind speed contributed to the observed reduction of blowing dust on the Southern High Plains.

Lubbock annual precipitation also shows no appreciable trend from 1961 to 2001 (Fig. 11). Annual precipitation varied from a maximum of 741 mm in 1969 to a minimum of 321 mm in 1970 with an average value of 470 mm and a standard deviation of 108 mm. Although there can be significant variation from year to year there are no major long-term trends that indicate significant shifts in precipitation.

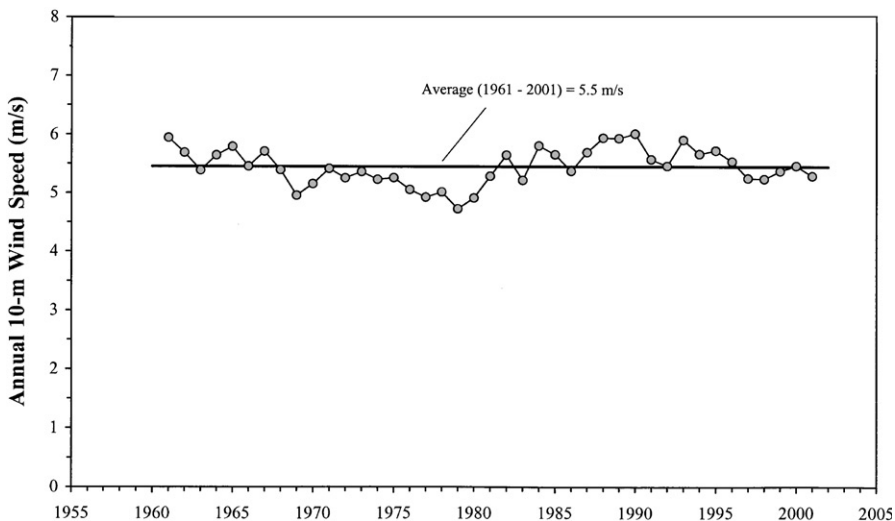


Fig. 10. Annual-average wind speed as reported by the Lubbock office of the NWS from 1961 to 2001.

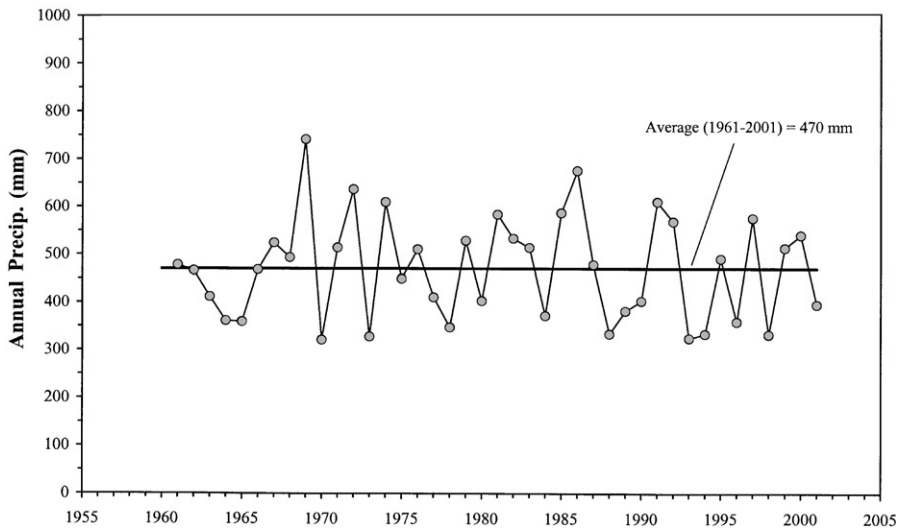


Fig. 11. Annual precipitation totals as reported by the Lubbock office of the NWS from 1961 to 2001.

Certainly, there is no major increase in rainfall that could account for such a significant reduction in ambient dust levels (compare Figs. 9 and 11).

The NWS typically reports relative humidity at 6 h intervals starting at midnight. These observations were averaged to obtain the annual average relative humidity for each year from 1961 to 2001 (Fig. 12). Annual relative humidity varied from a maximum of 64% to a minimum of 48% with an average value of 56% and a standard deviation of 4%. Results suggest that there can be minor yearly fluctuations, yet there is no evidence of any major long-term increase in relative humidity that could account for such a significant decline in ambient dust levels (compare Figs. 9 and 12).

Our analysis of past climate on the Southern High Plains is not exhaustive nor is it highly sophisticated. One could, for example, look at peak winds rather than average wind speed or at long-term changes in wind distributions. With respect to precipitation, one could look at the timing of rainfall events rather than total annual precipitation or at a drought index rather than rainfall alone. There are hosts of other data analysis techniques that might uncover less obvious climate shifts. However, minor climate shifts cannot fully account for the magnitude of the observed reduction in blowing dust. We conclude that climate has not played a significant role in the reduction of ambient dust levels on the Southern High Plains during the last four decades.

8. The role of land use

As farmers adjust cropping systems or take land out of production as participants in government conservation programs, they collectively modify the susceptibility of a

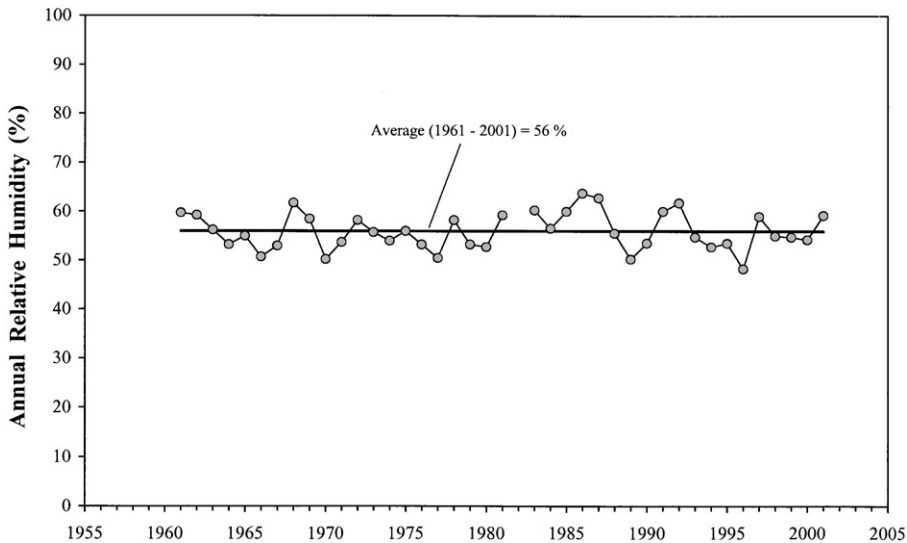


Fig. 12. Annual-average relative humidity as reported by the Lubbock office of the NWS from 1961 to 2001 (value for 1982 was not available).

region to wind erosion processes. What follows is an attempt to quantify land-use changes in the vicinity of Lubbock, Texas and determine whether such changes have contributed to the observed reduction of blowing dust.

Regional land-use information was obtained from the United States Census of Agriculture published by the USDA-National Agricultural Statistics Service. The Census of Agriculture provides uniform and comprehensive information regarding agricultural land use in the United States at the national, state and county level.

To describe land use in the vicinity of the city of Lubbock, information was collected for Lubbock County and eight surrounding counties including Hale, Floyd, Crosby, Garza, Lynn, Terry, Hockley, and Lamb (Fig. 13). The fraction of total cropland was determined by summing cropland for all nine counties and then dividing by the total area of all nine counties for each year that the Agricultural Census was published (Table 1). Cropland primarily refers to plowed land; however, it may also include cropland planted to cover crops such as legumes or soil improvement grasses to control erosion. Thus, to obtain an appropriate measure of the fraction of cropland susceptible to wind erosion, the relatively small fraction of cropland planted to cover crops was subtracted from the fraction of total cropland to obtain the fraction of “potentially erodible cropland”.

Results suggest that the potentially erodible fraction in the nine-county region has remained fairly constant from 1959 to 1982 (Fig. 14). During this period, the erodible fraction varied by less than 6% between census publication dates and overall it decreased less than 3% from 1959 through 1982. Measurements of annual TSP concentration, which began in 1961, show a decline of 40% from 1961 through 1982 (Fig. 14). Clearly, changing land use has played a minor role in the observed reduction of blowing dust from 1961 to 1982.

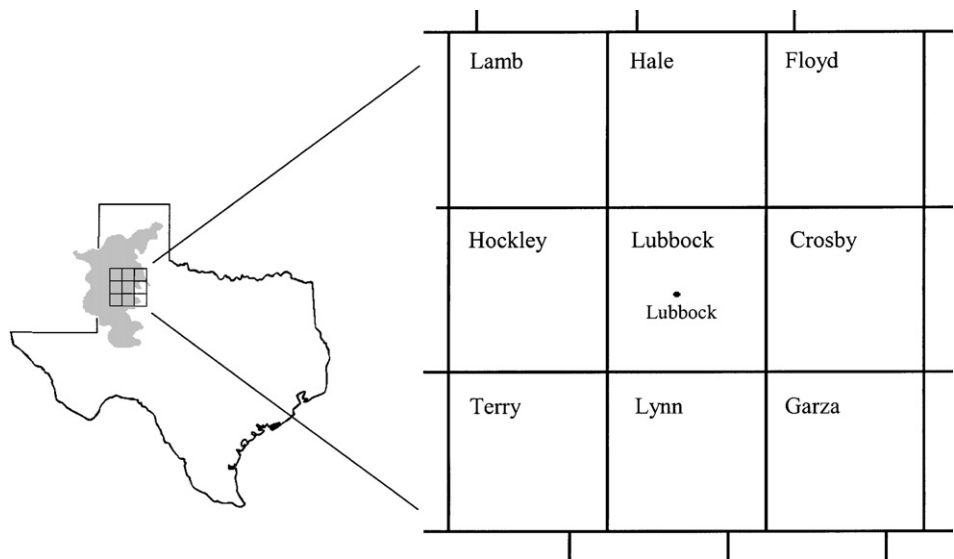


Fig. 13. Elevated ambient dust levels are generally associated with wind erosion activity in surrounding cropland. To describe land use in the vicinity of Lubbock sampling sites, information was collected for Lubbock County and eight surrounding counties.

Table 1
Summary of land use in a nine-county region including Lubbock, Hale, Floyd, Crosby, Garza, Lynn, Terry, Hockley, and Lamb counties from 1959 to 1997

	1959	1964	1969	1974	1978	1982	1987	1992	1997
Total cropland	0.70	0.71	0.74	0.66	0.70	0.68	0.62	0.63	0.65
Cropland planted to cover crops	0.03	0.04	0.05	0.01	0.02	0.02	0.08	0.08	0.06
Potentially erodible cropland	0.67	0.67	0.69	0.65	0.68	0.66	0.54	0.55	0.59

The fraction of total cropland and cover crops represents the sum for all nine counties divided by the total area of all nine counties. Potentially erodible cropland is the fraction of “total cropland” minus the fraction of “cropland planted to cover crops”.

There was a more significant decline of 18% in the fraction of potentially erodible cropland between 1982 and 1987, most likely associated with the 1986 introduction of the Conservation Reserve Program—a government program that pays farmers to convert highly erodible cropland to native grass cover for periods of 10–15 years. The reduction of potentially erodible cropland associated with the Conservation Reserve Program of 1986 appears to correlate well with a decrease in the reported hours of blowing dust from 1985 to 1987 (Fig. 2). However, annual TSP values show very little change from 1985 to 1987 (Fig. 9). A significant drop in annual TSP concentration is not observed until 1990 and this decline does not appear to be associated with a significant change in land use. In fact, the fraction of potentially erodible cropland increased 4% from 1987 to 1992 due to minor increases in total

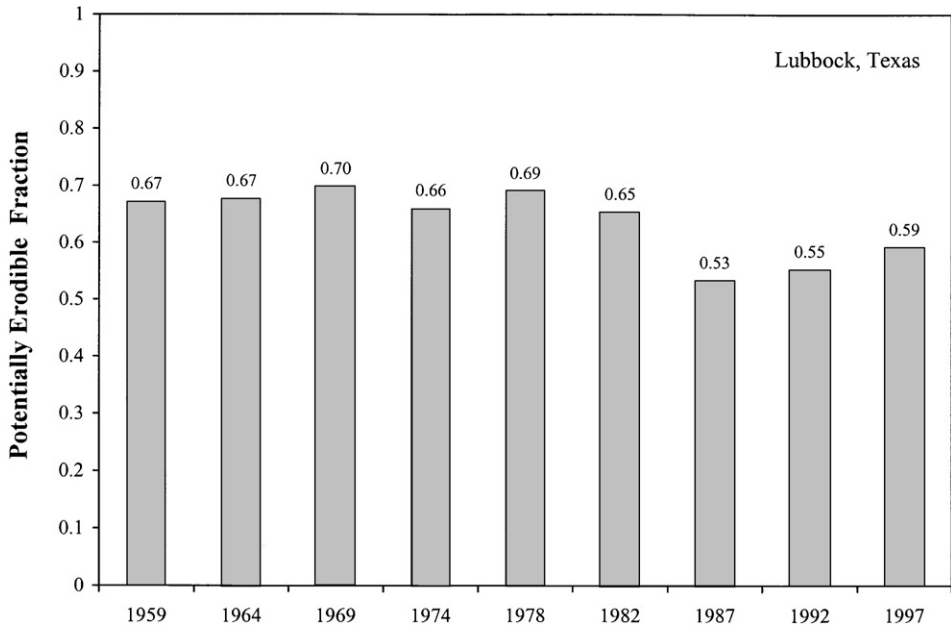


Fig. 14. Plot of the fraction of potentially erodible cropland in a nine-county region surrounding and including Lubbock County from 1959 to 1997. Potentially erodible cropland is defined as the fraction of total cropland minus the fraction of cropland planted to cover crops, such as soil improvement grasses or legumes.

cropland (Table 1) while annual TSP concentration decreased 35% during this same period (Fig. 9). Since an increasing erodible fraction is not consistent with a decline of ambient dust levels, factors other than land use contributed to the observed reduction of blowing dust from 1987 to 1992.

Overall it appears that there have been relatively minor changes in land use in the nine-county region surrounding and including Lubbock County from 1959 to 1997. The fraction of potentially erodible cropland reduced by only 11% during this period yet there has been a 70% decline in annual TSP concentration. One must conclude that changing regional land-use patterns have played a minor role in the reduction of wind erosion and blowing dust on the Southern High Plains during the last 40 years.

9. Summary and discussion

We have pieced together evidence of declining ambient dust levels at Lubbock, Texas, within the Southern High Plains of North America. Both visibility-based surface observations of blowing dust and direct measurements of particulate matter concentration independently suggest that there have been significant declines in blowing dust from 1961 to 2001. During this same period, there have been no substantial reductions in wind speed that could explain such a significant decline in

blowing dust. Precipitation and relative humidity have not changed appreciably so that it is doubtful that surface soil moisture has played a significant role in reducing blowing dust. In fact, there have been no appreciable climate shifts on the Southern High Plains that can account for the observed decline in blowing dust during the last four decades. Although it is not possible to rule out land use as a factor in the reduction of blowing dust in the Southern High Plains, one can point to periods when land use changed very little or potentially erodible acreage increased while annual dust levels decreased significantly. Overall, the relatively minor changes in land use, including the removal of land from production, cannot fully account for the observed reduction of wind erosion and blowing dust on the Southern High Plains. One is left to conclude that improvements in agricultural practices by individual farmers have collectively reduced the susceptibility of the Southern High Plains to wind erosion processes and these improvements, which are difficult to quantify, have significantly reduced wind erosion rates and dust emissions from 1961 to 2001.

Although there appears to have been substantial reductions in wind erosion and dust emissions, wind erosion remains a significant problem on the Southern High Plains. Thick aeolian deposits that form the upper-most soils of the Southern High Plains testify to the fact that this was a region of net deposition for many thousands of years (Gustavson and Holliday, 1999; Holliday, 1990); it was only within the last century that this process has been reversed (Worster, 1977). Although improved agricultural practices have reduced the destructive effects of wind erosion, the Southern High Plains remains a region of soil loss due to wind erosion and it will require much more work to return this region to its original condition of net sediment deposition.

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References

- Brooks, E., Emel, J., 2000. The Llano Estacado of the US Southern High Plains. United Nations University Press, New York, 176pp.

- Cowgill, D.M., 1970. Air Pollution Control 1970 Annual Report. Lubbock City-County Health Department, Lubbock, TX, 40pp.
- Environmental Protection Agency, 1969. Air quality data for 1967 from the National Air Surveillance Networks and contributing state and local networks. National Air Pollution Control Administration Publication No. APTD 69-22.
- Ervin, R.T., Lee, J.A., 1994. Impact of conservation practices on airborne dust in the Southern High Plains of Texas. *Journal of Soil and Water Conservation* 49, 430–437.
- Godish, T., 1985. Air quality. Lewis Publishers, Chelsea, MI, 372pp.
- Goklany, I.M., 1999. Clearing the air. *The Real Story of the War on Air Pollution*. Cato Institute, Washington, DC, 187pp.
- Goudie, A.S., 1983. Dust storms in space and time. *Progress in Physical Geography* 7, 502–530.
- Goudie, A.S., Middleton, N.J., 1992. The changing frequency of dust storms through time. *Climatic Change* 20 (3), 197–225.
- Gustavson, T.C., Holliday, V.T., 1999. Eolian sedimentation and soil development on a semiarid to subhumid grassland, Tertiary Ogallala and Quaternary Blackwater Draw formations, Texas and New Mexico High Plains. *Journal of Sedimentary Research* 69 (3), 622–634.
- Holliday, V.T., 1990. Soil and landscape evolution of eolian plains: the Southern High Plains of Texas and New Mexico. *Geomorphology* 3 (3), 489–515.
- Holliday, V.T., 1995. Stratigraphy and paleoenvironments of late Quaternary Valley Fills on the Southern High Plains. *Geological Society of America, Memoir No. 186*, 136pp.
- Hurt, R.D., 1981. *The Dust Bowl. An Agricultural and Social History*. Nelson-Hall, Chicago, IL, 214pp.
- Lee, J.A., Allen, B.L., Peterson, R.E., Gregory, J.M., Moffett, K.E., 1994. Environmental controls on blowing dust direction at Lubbock, Texas, USA. *Earth Surface Processes and Landforms* 19, 437–449.
- Offer, Z.Y., Goossens, D., 2001. Ten years of aeolian dust dynamics in a desert region (Negev desert, Israel): analysis of airborne dust concentration, dust accumulation and the high-magnitude dust events. *Journal of Arid Environments* 47 (2), 211–249.
- Opie, J., 1993. *Ogallala. Water for a Dry Land*. University of Nebraska Press, Lincoln, NE, 475pp.
- Orgill, M.M., Sehmel, G.A., 1976. Frequency and diurnal variation of dust storms in the contiguous USA. *Atmospheric Environment* 10, 813–825.
- Pecille, J.A., 1973. Wind and dust study for Lubbock, Texas. NOAA Technical Memorandum NWS SR-70, US Department of Commerce.
- Reeves, C.C., Reeves, J.A., 1996. *The Ogallala Aquifer (of the Southern High Plains), Vol. 1—Geology*. Estacado Books, Lubbock, 360pp.
- Simiu, E., Scanlan, R.H., 1978. *Wind Effects on Structures. An introduction to Wind Engineering*. Wiley, New York, 458pp.
- Stout, J.E., 2001. Dust and environment in the Southern High Plains of North America. *Journal of Arid Environments* 47 (4), 425–441.
- Todhunter, P.E., Cihacek, L.J., 1999. Historical reduction of airborne dust in the Red River Valley of the North. *Journal of Soil and Water Conservation* 54 (3), 543–551.
- USDA-National Agricultural Statistics Service, 1997. *Census of Agriculture*.
- Wendorf, F., 1961. *Paleoecology of the Llano Estacado, Vol. 1*. The Museum of New Mexico Press, Santa Fe, Fort Burgwin Research Center Publication, 144pp.
- Wigner, K.A., 1984. Dust storms and blowing dust on the Texas South Plains. M.S. Thesis, Texas Tech University, Lubbock, TX, 151pp.
- Wigner, K.A., Peterson, R.E., 1987. Synoptic climatology of blowing dust on the Texas South Plains 1947–84. *Journal of Arid Environments* 13, 199–209.
- Worster, D.E., 1977. Grass to dust. *Environmental Review* 3, 2–13.
- Worster, D.E., 1979. *Dust Bowl: The Southern High Plains in the 1930s*. Oxford University Press, Oxford, 277pp.